Microdose Induced Data Loss on Floating Gate Memories

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***Abstract*—Heavy ion irradiation of flash memories shows loss of stored data. The fluence dependence is indicative of microdose effects. Other qualitative factors identifying the effect as microdose are discussed. The data is presented, and compared to statistical results of a microdose target-based model.**

***Index Terms*—Flash, floating gate, microdose, SEU.**

I. Introduction

FLOATING GATE (FG) based memory technologies, such as EEPROM and flash are critical to most space flight programs due to their extreme density and non-volatility. They are used in a wide variety of spacecraft subsystems. At one end, flash memories are used to store small amounts of mission critical data such as boot code or configuration files. On the other end of the spectrum, flash memories are used to construct large (multi-gigabyte to terabyte) data recorders that are used to record mission data. In data recorder applications, flash devices have a distinct advantage over tape and disk drives, which achieve competitive densities and are also non-volatile. However FGs are completely solid state, and thus require no moving components. Data recorders comprised of flash memories are mechanically simpler, and thus more mechanically reliable than traditional drives. Unfortunately, the functionally of FG devices is sensitive to the presence of radiation fields, which are encountered in most space flight programs.

To internally generate the large programming and erasing voltages, charge pump circuitry with relatively thick oxides is often employed. The functionality of these structures begins to fail as total ionizing dose (TID) accumulates during a space mission. In addition, direct strikes from galactic cosmic rays (GCR) and protons from a solar flare or magnetosphere can upset internal digital circuitry such state buffers, cache, or state machines. These upsets can result in incorrect read/write operations or even cause the device to not function until it is power cycled, reinitializing all the internal circuitry. Flash devices are not as sensitive to data loss, or bit upsets induced by single event effects (SEE), such as those experienced by SRAMs and DRAMs, because the information on FGs are embedded by the presence or absence of trapped charge on an electrically isolated conductor.

However, many recent studies have focused on radiation-induced leakage of the trapped charge from "programmed" FG, i.e., gates with trapped charge. That is, FG's were programmed to their charged state, where they hold excess electrons, then exposed to TID, and then observed to have a non-zero current of FG electrons leaving the FG. These studies have shown the loss of information from FGs to be a result of both the accumulation of ionization from gamma rays and individual ion strikes [1]–[7]. Much of the previous work measured the shifts in distributions of voltage thresholds of programmed FG MOSFETS as a function of heavy ion fluence. It was discovered that the shifts became greater in time, and a model was formulated predicting that radiation-induced damage in the oxide isolating the FG from the FET gave rise to long term small, but non-negligible trap-assisted tunneling current that resulted in loss of charge from the FG. Thus, over time the threshold shifts became larger, as charge slowly leaked off the FG into the bulk of the device. Radiation has also been seen to cause immediate voltage threshold shifts in flash devices. Only the Strata Flash™ structure, with its multi-level storage elements, has been observed to show upsets due to this shift [9].

Much of the modeling, and previous observations of cell effects in flash memory were done on NOR flash memory. This work deals with NAND flash memory. The cell structures are similar in the sense that there is a Control Gate (CG), oxide, Floating Gate (FG), oxide, substrate sandwich. The NAND structure uses buffering and page programming to improve performance, and therefore is much more susceptible to SEE. Results of radiation effects testing of NAND and NOR memories can be found in other papers [9]–[13]. These show roughly equivalent TID response, and find most SEE effects to be the result of radiation effects on the control circuitry.

We performed heavy ion irradiations on NAND flash devices, and also observed the loss of information from programmed bits. However, due to the fact that commercial devices were used, we could not measure the threshold shifts. The only indication we had that the ion strikes affected the programmed bits were in the cases where the voltage threshold shifted enough (from the loss of charge) so that the sense amp circuitry associated with each bit could no longer resolve the bits as logical '0's, but reported them instead as a logical '1's. Some of the deprogrammed cells showed post radiation characteristics inconsistent with the previously published results and models.

II. Background

Irradiation of flash memory cells for single event effects has historically yielded few results that can be isolated to true cell effects. Flash memory cells are very difficult to test in SEU environments because control circuitry responds to radiation much more readily than cells. Given the fact that flash memories continue to house an increasingly complicated set of voltage gener-

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ators and operational logic, this is a tendency that is not likely to change. Isolating radiation effects on cells is further complicated by the fact that for the most part flash memory cells are insensitive to SEE. This is inferred from the sensitive structures (loss of charge from the FG, rupture in the oxides, charge trapping in the oxides, etc.) and the lack of solid data showing any of these to have been susceptible to radiation effects in the past. Certainly these structures can all experience SEE phenomena, but previous data suggest that the phenomena do not cause a large enough effect to be observed [9]–[12]. In order for a flash cell to be affected, an ion strike would have to either significantly damage the cell, or remove enough charge from the FG to be observed. Both effects are referred to as upset, but can also be thought of as deprogramming the cell.

Because of the testing problems of flash memory, cell testing is usually done on either test structures, or on test devices operated in a static mode. Very little evidence of flash memory data loss has been observed on commercial devices, as suggested above. Thus most of the useful cell results come from test structures.

Cellere and collaborators have used test structures along with models to show how radiation can result in lost charge on floating gates [1]–[6]. In those works, test structures were exposed to enough TID to make the oxides in the test structures start conducting current. The TID was applied in two radiation types. The first type is flat dose, where the TID exposure is uniform. The second type is heavy ion irradiation where the TID is applied at the locations of the ion strikes. In the heavy ion irradiation, only large LETs caused deprogrammed bits.

Heavy Ion irradiations were performed on Samsung 2 Gb NAND flash memories. Previous work on flash memory has demonstrated that the only radiation effects showing clear FG cell response are: marginal shifting of voltages, and the creation of very small leakage currents. The former occurred only in a very small set of test devices, while the latter has been heavily modeled.

Modeling and TID testing has shown that leakage current is developed in TID exposure. This leakage current, although usually quite small, can remove the stored charge from the FG, and was one of the effects directly targeted by this study.

The basic structure used in the modeling of the induced leakage currents, as well as the corresponding SEM images for the DUTs, are shown in Fig. 1. The elements of the flash cell are shown. They are: (1) Control Gate (CG), (2) Oxide-Nitride-Oxide sandwich (ONO), (3) Floating Gate (FG), (4) Tunnel Oxide (TO), and (5) the Substrate.

Based on these structures, the FG cells appear to be susceptible to several possible types of radiation induced data loss. The radiation effects that can result in changing the stored data are:

a) FG loses charge—prompt loss;
b) FG loses charge, but due to very small leakage current;
c) The oxides store charge and mask the FG;
d) One of the oxides is ruptured.

III. Test Setup

For this paper, we tested modern flash memories with heavy ions and found them to exhibit cell level data loss. Although several types of data loss have been observed in the literature, we believe the particular mechanism of this data loss is somewhat novel compared to those that have been modeled and observed in the past.

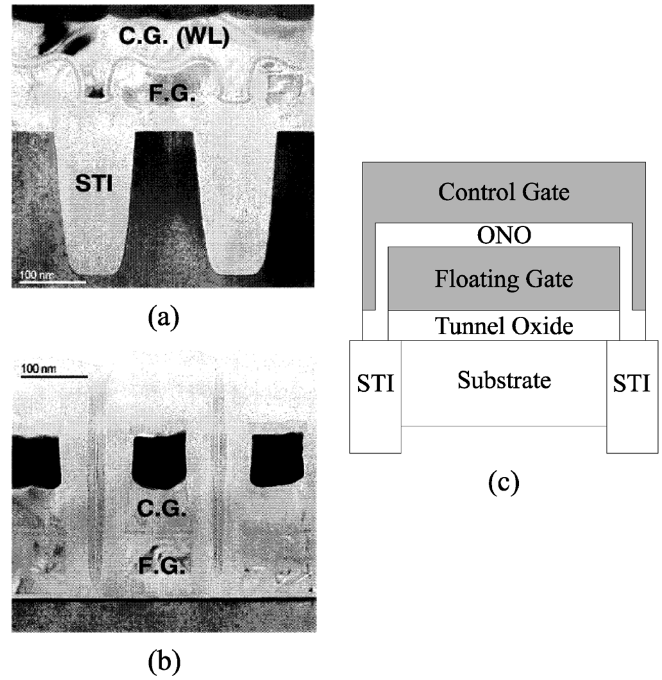

Fig. 1. Left: Cross-sectional SEM images of the 2-Gb NAND Flash cell; (a) wordline direction, (b) bitline direction (see [8]). Right: (c) sketch of industry standard Flash cell, as used in [5].

TABLE I
Ions Used in Testing

Ion	Facility	Energy/amu (MeV)	Incident LET MeVcm^2/mg
Ne	TAMU	25	1.77
Ar	TAMU	25	5.7
Cl	BNL	6	11.4
Kr	TAMU	25	20.3
Ni	BNL	4.6	26.6
Br	BNL	3.5	37.5
Xe	TAMU	25	40
Ho	TAMU	15	68.4

Testing was conducted at both the Texas A&M University Cyclotron facility, and at the Brookhaven National Laboratory Tandem Van de Graff facility. The ions used at the facilities are listed in Table I. The ions used provided a wide range of LETs, but also provided a wide range of energy per amu, which may have had some affect on the observed data. This is particularly true if the ion has some risk of ranging out, or stopping, in a sensitive region of the DUT, such as with Ni and Br.

The DUTs were etched to remove the plastic packaging and expose the memory array to the ion beams. They were tested using an embedded FPGA-based tester designed to be connected directly to the DUT. The tester and DUTs were powered separately by an HP6629 power supply. Operation of the tester, and data transfer was carried out via an RS232 connection to a laptop computer. This setup allowed for rapid detection and protection from single event latchup events, and storage of the first 250 error addresses.

In order to test the DUTs the following algorithm was used:

1) DUT is powered;
2) DUT is erased (or programmed to "all 1's");
3) DUT is programmed to "all 0's";
4) DUT is put into "test configuration"—usually unbiased;
5) DUT is irradiated;
6) DUT is read to count "0's" that changed to "1's";
7) After various annealing periods, (6) is repeated.

TID was an issue in this testing. The DUTs used have fairly low TID tolerance, especially when compared to the very high fluences used at low LET. Although the DUTs are expected to survive upwards of 20–40 kRads, care was taken to ensure that TID effects on the control circuitry did not interfere with the test results. One device was observed to be behaving erratically, in this manner, at very low TID, but had in fact been exposed to 15 kRads before the heavy ion testing started.

The cross section for a particular event type can only be well defined if there is a constant proportionality between a given fluence and the number of errors that the fluence causes. So that 10 times the fluence results in 10 times the number of events observed.

For many of the LETs cross section could not be defined because the observed errors were not proportional to the fluence. For that reason, we determined it would be useful to take data where the fluence varied over several orders of magnitude. Because of the TID limits of the DUTs and minimum fluxes required by the facilities, there are limits to the range of fluences to which the DUTs were exposed. Where possible, though, we tried to expose DUTs to fluences ranging over 3 orders of magnitude.

IV. Results

The primary experimental results are the measurements of flash cell upsets across the various beams, and annealing data taken by observing the number of upset cells change as a function of time after irradiation. Those results are presented shortly, but first it makes sense to give a description of more qualitative experimental results.

A. Qualitative Results

Flash memories are known to exhibit corrupted cells due to disruption of control circuitry. That is of major concern because it makes it very difficult to observe true cell effects. In order to isolate cell effects much of the data was taken with the DUTs unbiased. The reasons are the following. First, when irradiated while operating, flashes have been known to upset their stored data by triggering write or erase operations. Second, even when a flash memory is biased, because of the string size of 32 bits, only 67 584 bytes are biased during page operations. This is only 1/4096th of the DUT. The remainder of the DUT then remains unbiased. Third, unlike volatile memories, bias is not needed to maintain stored data.

In order to verify that presence or lack of bias did not affect the results presented, several test runs were made with devices in alternate bias states. That is, test runs were made once with a given DUT biased, and once with it unbiased, to verify bias dependence. Bias dependence was tested specifically for Ar, Cl, Ni, Kr, and Br. See Table I for the list of test ions. The lower LET ions provided smaller deviations from the biased results.

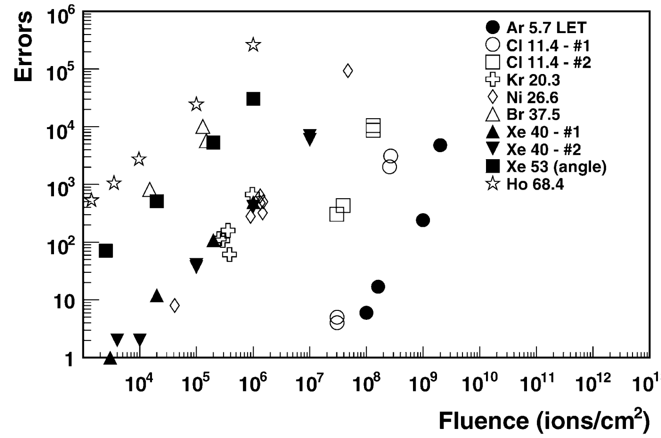

Fig. 2. Deprogrammed bit results. Data was observed to follow a power-law relationship and thus was taken over several orders of magnitude for the same ion species, because sometimes the power law fit resulted in an exponent above unity.

The data suggest that unbiased irradiation results in somewhat fewer (between 10% and 40% fewer) deprogrammed bits, but the difference is not very big. For example some of the Cl results show 10% lower number of upsets for unbiased, while other data shows a slightly higher number of upsets for unbiased. This inconsistency should be treated as a systematic error, and not as a clear bias dependency. To reduce damage to supporting circuitry, limited irradiation was done under bias, so this is presented as only a qualitative result. Aside from this test, which was limited, all other irradiation was performed on unbiased DUTs.

It must be verified, however, that the upset data being observed is actually cell upsets, and not damage to control circuitry. The best way to test this is to observe the distribution of the upsets throughout the device. By checking error files randomly, we determined that each of the 2048 blocks contains roughly 1/2000th of the errors. Errors were observed to occur most often in only 1 bit of the data associated with a given address. The upset bit could be any bit from 0 to 7 in the stored byte.

Low LET data gathering showed that the number of upsets caused by a given fluence is not proportional to the fluence that caused the upsets. This is seen in Fig. 2, which is discussed later. This effect disappears as the LET increases. This result is quantitatively presented in the next subsection. This is a key observation, and led to taking data across many fluences.

There is also an apparent lack of a minimum LET at which cells are deprogrammed. A little low LET data was taken, and only a single event was observed with 2×10^8 Ne ions $(\mathrm{LET} = 1.77\ \mathrm{MeV} \cdot \mathrm{cm}^2/\mathrm{mg})$. Based on the expected ionizing dose due to the various ions, and the observation of only one event, it is believed that TID to the entire device might render additional data taken with Ne unreliable. However, the dataset could benefit by taking additional data at this low LET.

The final qualitative experimental result to discuss here is the observation that the erasing operation "repairs" a damaged FG cell. I.e., upon reprogramming a de-programmed bit, the bit will be stable in the '0' state. It should be noted, however, that the reliability of such cells over normal flash storage timescales was not explored.

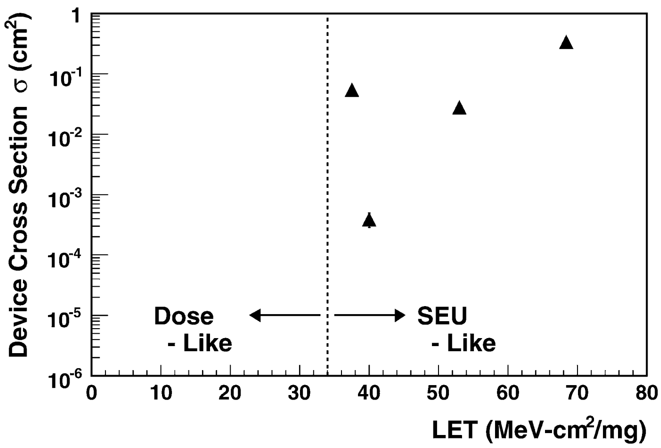

Fig. 3. For datasets from Fig. 2, if the observed power law relationship is linear (the power law fit gives an exponent of unity), then cross section is well defined. This is the case for LETs above 37 $\mathrm{MeV} \cdot \mathrm{cm}^2/\mathrm{mg}$. Below 37, the effect still exists but does not behave like SEU, so we call it "Dose-Like".

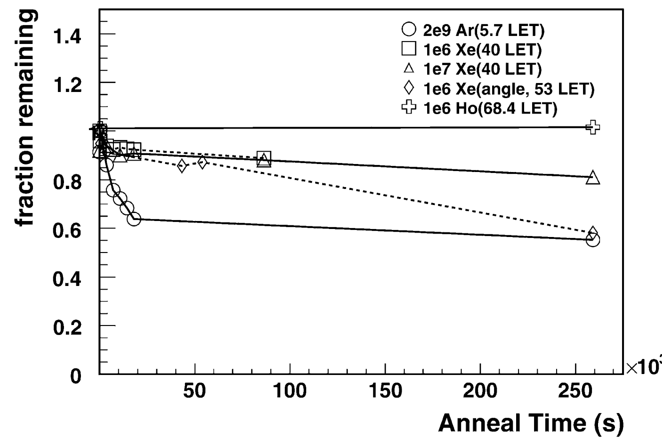

Fig. 4. Long term annealing results are shown. Annealing does not show appreciable increase in number of deprogrammed bits with time.

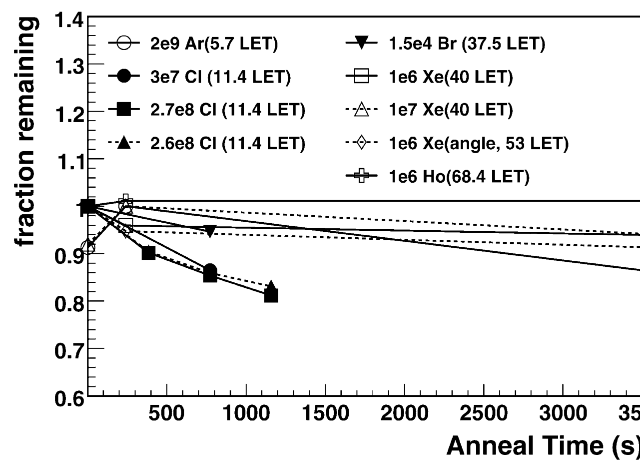

Fig. 5. Short term annealing results are shown. This figure highlights the problem of defining the normalization at short time intervals.

B. Quantitative Results

Deprogrammed bits were observed with all of the ion species listed in Table I. Some were tested at angle, and some across multiple DUTs. Except for Ne, the results of deprogrammed bit, or error counts, are given in Fig. 2. For this figure, the error counts were made between 3 and 6 minutes following the end of the beam run.

This variation in measurement time is due to a combination of operator, facility, and test equipment-related effects, described in the following. Upon completion of the irradiation, the facility has to inform the test operator, after that the test operator must instruct the software to interrogate the stored data. Also, the test system itself takes time to finish, and an upgrade in the test system cut the full read time from 5 minutes to about 3 minutes. Thus, the effective read time could vary from 3 to 6 minutes after the end of the radiation exposure.

It is of particular interest to note that if the slope of a data set in this figure is 1, then the cross section is defined. The slope related to LETs below 37 $\mathrm{MeV} \cdot \mathrm{cm}^2/\mathrm{mg}$ is always above 1 (see Microdose Modeling, Section VI), so cross section cannot be defined there, but upsets were still observed.

For those data sets where cross section is defined, we calculated it, and plotted it in Fig. 3. If the cross section cannot be defined, that is, if number of upsets was not linear with fluence (i.e., the power law fit is greater than unity), upsets are considered "dose-like". Thus, Fig. 3 is a standard cross section versus LET plot. Unfortunately it cannot be made explicitly clear that upsets still occur below the lowest data point, but we have added a line and pointed out that the upsets are dose-like below LET 37. Upsets still occurred at all tested LETs below 37, but cross section could not be defined. The Br result in Fig. 3 is anomalous (the high point at 37.5 LET). One possible explanation for it is due to the very short range of Br compared to the other ions. If it were stopping in the flash cell this might seem reasonable, but the Br range should be long enough to get through, however, it was tested in air, so the range is in question.

Since the effects are expected to be dose-related, it makes sense to study annealing effects. In particular, it makes even more sense here because although annealing might occur, there are TID results [1]–[6] that suggest leakage paths might be slowly removing charge from the FG, and result in an increasing number of deprogrammed cells as a function of time. The results of a limited long-term annealing study are shown in Fig. 4. This figure shows little evidence that the number of deprogrammed cells might be increasing. However, there are large periods of time where the number of upsets is not measured, but seems to be fairly constant, which could also be consistent with a dip followed by a rise.

Some additional measurements were taken a week or more after the last data points shown. They show some variation compared to what is seen in Fig. 4. but do not suggest a general trend toward increasing the number of deprogrammed cells. One device did show a large increase after 2.5×10^5 s, but it is behaving like an outlier. Also, the Holmium (Ho) dataset provides a consistent, but nearly negligible increase with time. The Ho results have increased in number of deprogrammed cells by about 1500 upsets per week, or about 0.8% per week. Since Ho is the highest LET ion, it may provide a useful place to compare with some of the other published results that rely on high LETs to produce the leakage currents that deprogram the FG.

Fig. 5 is included to show some of the difficulty with establishing the basis for annealing measurements. Measurements cannot reliably be made while irradiating, because of the tendency for functionality upsets during irradiation. Hence upset counts had to be made after the irradiation ended. Also, since the upsets are believed to be due to microdose, it is likely that some of the effects of the TID do not settle until some time after irradiation. Thus, following irradiation, we start the process of counting errors, so that the first interrogated bits are observed $\mathrm{t} = 0$ seconds after irradiation, and the last bits are interrogated $\mathrm{t} = 400$ seconds after irradiation. To make the situation more delicate, our test system was upgraded in between some of the testing and the full cycle time was reduced from about 400 seconds to about 200 seconds. Thus the $\mathrm{t} = 0$ point in Fig. 5 is actually whatever time the first read pass ended, and is not well defined. Hence some leeway is needed in selecting the normalization.

These problems all combine to give the short time scale effects seen in Fig. 5. In order to provide useful results, the "base" number of upsets on which to fix annealing effects is generally taken to be the peak in the first 500 seconds. The Holmium (Ho) ion irradiation result (which is not normalized to 1) was allowed to exceed this because it keeps the figure clear.

These data show TID results that are caused by heavy ions. These results also have hallmarks of SEE effects because, provided the deposited TID is large enough, a single ion can cause a bit change. Because of the microdose nature of these TID exposures, to get similar behavior from a Co-60 or proton-type TID exposure, the DUTs would have to be exposed to 1 000 to 10 000 times the total device TID needed for these experiments. At those levels (more than 5 MRads), these devices would no longer work. However, if one could obtain test structures, these results could be tested against uniform TID on those structures.

V. Discussion

The primary purpose for this section is to explain why the observed upsets appear to be the result of microdose. That is, we will layout the argument for claiming the results are TID, and therefore microdose, related. Once that argument is made, we will explain how the very small LET ions cause upsets, and we will discuss why the fluence dependence of upsets is not necessarily proportional. This will lead into Section VI where simulations are made, based on items discussed here.

Perhaps the single biggest observation that suggests microdose effects here is the presence of annealing results showing some cells recover to the programmed state. In particular, these cells are first programmed, putting electrons on the FG. After that, the voltage of the FG is low enough to mask the read voltage on the CG, and keep the transistor below threshold; hence a "0" is read. After irradiation the oxide layers and FG do not have a charge distribution capable of masking the control gate. The cell then reads out as "1", or unprogrammed. Some time after this, the system spontaneously reverts back and reads out a "0".

Barring radiation damage to the CG or the Substrate, the radiation effect must have been on one of the remaining structures. The annealing result explicitly requires that the FG did not get deprogrammed. It may have lost some charge, but in general it must retain most of its charge in order to recover the programmed state after annealing.

Thus something happened to the oxides that made the FG unable to mask the control gate for a period of time. Hence charge must have been deposited in one or more of the oxides.

Because reading is performed by biasing the CG while the floating gate contains some stored charge Q, all that is required for the transistor channel to experience an altered electric field is for the charge distribution of the oxides and FG to change. Thus, although recombination would cause the annealing result, all that is necessary is for some of the trapped holes to migrate towards the top of the ONO-FG-TO sandwich. Doing this, especially in the ONO, will reduce the amount of charge required by the CG to maintain its voltage, and hence allow the FG to have greater influence.

Thus the results are consistent with TID effects. The reason they must be microdose is because of the source of the TID. Heavy ions can only deposit ionizing dose in cylinders around the ion path through the material.

It is possible, given the effect being due to TID, that a lower LET ion strike will not deposit enough ionization to cause a cell to be upset, but two strikes could deposit enough. In this case the probability of an upset is not proportional to the probability that the cell is struck. If the probability that a cell is struck is p, then the probability that the cell is struck twice should be p^2. A simulation of multiple strikes is presented in the next section. Here, though, we would like to point out that if multiple strikes are necessary, cross section cannot be defined. When plotted as in Fig. 2. ions requiring more than one hit will have a slope steeper than 1.

VI. Microdose Modeling

Modeling of the flash structure and ion strikes, in order to form a picture of how various LET ions affect the cells is a logical next step. Before doing that, though, it made similar sense to us to understand what type of cell effects could possibly be giving rise to the fluence dependence of the data. After that, the next step would be to analyze the effective charge distributions due to various LET ions, and the resulting annealing behavior, to see if the simulations matched our data.

We concluded in the section above that the cell upsets are due to microdose. Here we present a discussion of how the microdose is likely causing the non-linear behavior in the fluence dependence, by using a statistical modeling framework. The non-linear dependence is postulated to be due to multiple TID depositions. However, the dependencies that were found did not go as Poisson probabilities might suggest. Because of this, we decided to model the system in such a way as to test the regions where Poisson begins to break down, namely when the probability of a hit is large.

The simulation was based on Monte Carlo techniques. A large array was created and sample hits were made. Based on the number of hits thrown, and the frequency with which cells collected various numbers of hits, statistical data was collected.

Simulations were done with a C++ routine, and used the gcc (gnu compiler collection) random number generator. The simulations involved making a target array and throwing hits at it. Each hit would only hit one target for the simulation. The number of hits on a given target was counted and binned across all targets to gather statistical observations. Array size

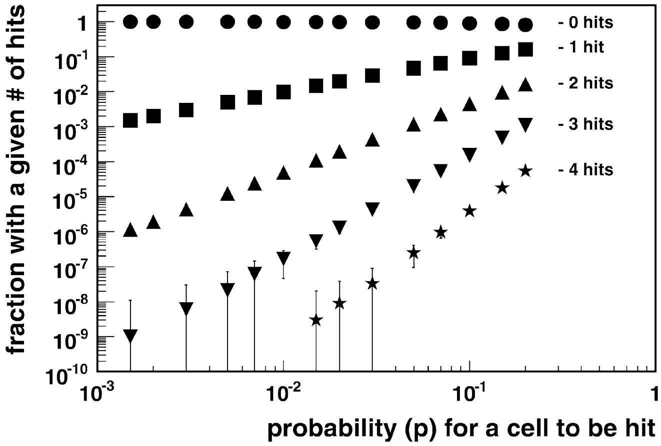

Fig. 6. Results of montecarlo modeling of cell hits. The families of points represent the relationship between probability for a cell to be hit compared to its probability to be hit n times.

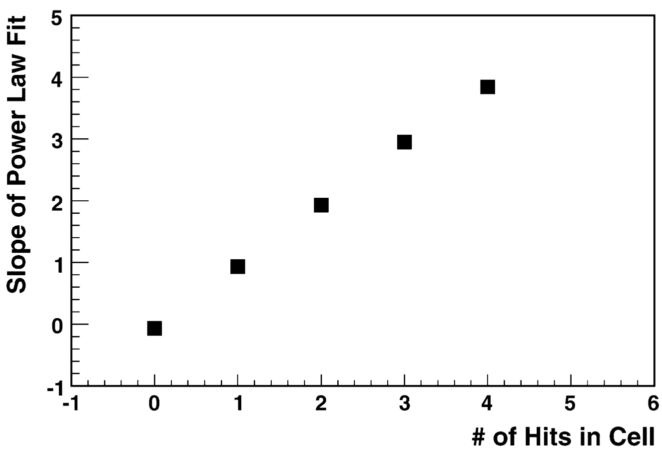

Fig. 7. The power law relationships for the families of curves in Fig. 6. are pottend. These show the relationship is p(n hits in a cell) = p(1 hit in a cell)^n.

was varied from 10 000 targets to 10 000 000 targets to verify that the statistical significance observed was less than the granularity of the algorithm and numerical precision used. The results are shown in Figs. 6 and 7. Fig. 6 shows a family of curves for the frequency of the number of hits observed in a cell. With the number of simulations, algorithm, and array size used, the results are only really useful for cells with 4 or fewer hits. Fig. 7 shows the power law relationships between the various curves. This figure verifies that the simulation is reproducing Poisson statistics, provided the actual probability of an event is below 10%.

The results in those figures fit the expected behavior of multiple hits to the same cell, and also have a qualitative behavior similar to Fig. 2. The curves in Fig. 2 were matched to power law fits, and the results are given in Table II. However, the real data does not show the normal Poisson probabilities found in the modeling. The modeling does allow for deviation, but only in the last decade of the results where the probability is above 10%. Since the real data covers several orders of magnitude, this is not a reasonable explanation.

Because of the range of the real data, and the lack of a match to the modeling, it is unlikely that the results are really just 2 or 3 hits. Rather, there is probably a multiple cell effect going on, or the hits are not identical. These scenarios should both be verified, but it is expected that they behave for the most part as the already modeled results, due to the fact that they still require 2 hits or more.

TABLE II
RESULTS OF POWER LAW FIR FOR DATA SETS

Ion & LET MeVcm^2/mg	Fitted Power	χ^2 / NDF
Ar 5.7	2.33±0.10	62.0 / 2
Cl 11.4 #1	2.94±0.15	3.37 / 2
Cl 11.4 #2	2.41±0.09	3.38 / 2
Kr 20.3	1.49±0.14	24.5 / 3
Ni 26.6	1.46±0.03	26.0 / 5
Br 37.5	0.984±0.066	22.8 / 1
Xe 40 #1	0.979±0.073	0.693 / 2
Xe 40 #2	1.12±0.03	4.28 / 5
Xe 53 -angle	1.02±0.03	0.792 / 2
Ho 68.4	0.955±0.02	3.17 / 3

It should be noted that the modeling results are consistent with Poisson statistics, and predict that the slopes found in Table II should be integers if, indeed, the effect requires an integer number of hits to the same cell. The reality of the multiple hit problem here is that there are likely multiple structures in the flash cell that can provide the second hit, and thus the effective cross section for the first hit is much different than for the second hit. Also, it could be that some of the cells require 2 hits while the others require 1 because of tolerances.

VII. REVIEW

There are a few inferences that can be drawn from the results. There are also some points to clarify, should one be interested in extending this work. This section will serve to highlight those points.

The structure of the floating gates in the test devices is consistent with the qualitative behavior of the data (structure details given in [8]). That is, the oxides present in the cell design, and the layout of the floating gate, allow for the observed effects. The data is consistent with microdose deposited in the oxides of a flash cell. Furthermore, the data strongly suggest TID deposition from multiple ion hits is important at lower LETs, and gives rise to the fluence dependence of the deprogramming, or upset, rate. However, at higher LETs the same argument for microdose cannot be made. At higher LETs, then, the qualitative behavior that supports a microdose picture is that deprogrammed cells can anneal back to the programmed state.

The short term annealing results are inconsistent with previous published data. This is because annealing in NOR flash cells, as well as arguments for slow leakage currents, both suggest that the data in flash cells should continue to degrade with time, and not show recovery. On short time scales, however, some of the deprogrammed cells show recovery of their programmed state.

There are several avenues to extend this work. For example, the data in the community suggests that the decrease in deprogrammed cells with annealing is a trend that should actually rebound at larger time scales. Such a rebound will be dependent upon competition between charge neutralization or reconfiguration in the oxide(s), and leakage current through the oxide. Longer anneal measurements on these devices are, therefore, suggested.

Longer anneal measurements are also recommended if the devices are to be used without refreshing their contents. This is because these devices were really not studied in this way, and the risk that long term leakage currents are set up by radiation should be assessed.

It should be noted that we observed bits become deprogrammed at extremely low LETs (as low as $1.77\ \mathrm{MeV \cdot cm^2/mg}$). Again, this is inconsistent with the previous published data, which required relatively high LETs and large fluences to deprogram a handful of bits

If flash memories such as those tested here are selected for use in radiation environments, the application should consider refreshing them. Erasing and rewriting the cell easily restored cell data. Also, because of the large electric fields and forced charge movement involved in erasing and writing, TID accumulation below that needed to upset a cell can be wiped clean by rewriting the data. However erasing and writing expose the device to high internal voltages that can cause catastrophic failure in radiation environments.

VIII. Conclusion

The tested 2 Gb NAND flash memories exhibited loss of programmed bits as a result of heavy ion irradiation. A cross section could not always be properly defined and the behavior is indicative of TID accumulation. Since the TID was applied to small volumes, by heavy ion strikes, the behavior was analyzed in terms of microdose.

Qualitative tests were done to isolate the observed effects. These tests highlight the observed upsets as cell effects. They also provided support to the TID prescription, rather than traditional SEEs that would discharge or damage the cell.

The results were analyzed and modeled to probe the nonlinear relationship of observed deprogrammed bits with fluence. Due to lack of sophistication in the model, the modeling work was only able to verify that the TID dependence is inconsistent with single hits.

These observations are novel, as they require the radiation effects to occur at the cell level, which has been very difficult to isolate in NAND flash. However, they also suggests an increase in the types of radiation effects that can cause degradation of stored data on an otherwise healthy part. This is especially true given the observation that leaving devices unbiased did not significantly improve their response.

The observed susceptibility to microdose effects might be indicative of standard flash cell response coming in future generations. This is likely a result of the shrinking feature size, oxide thickness, and the number of electrons trapped on the floating gate (thus tolerances of control circuitry). As Flash cell sizes are decreased; the deprogramming of bits is expected to become more significant. Thus understanding the nature of microdose "effective" charge loss is significant.

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